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Analyzing fair access to urban green areas using multimodal accessibility measures and spatial prioritization

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ABSTRACT

Maintaining enough green areas and ensuring fair access to them is a common planning challenge in growing and densifying cities. Evaluations of green area access typically use metrics like population around green areas (within a certain buffer), but these do not fully ensure equitable access. We propose that using systematic and complementarity-driven spatial prioritization, often used in nature conservation planning, could assist in the complex planning challenge. Here, we demonstrate the use of spatial prioritization to identify green areas with highest recreational potential based on their type and their accessibility for the residents of the Helsinki Metropolitan area, the capital district of Finland. We calculated travel times from each city district to each green area. Travel times were calculated separately to local green areas using active travel modes (walking and biking), and to large forests (attracting people from near and far) using public transport. We prioritized the green areas using these multimodal travel times from each district and weighting the prioritization with population data with Zonation, conservation prioritization software. Compared to a typical buffer analysis (population within a 500 m buffer from green areas), our approach identified areas of high recreational potential in different parts of the study area. This approach allows systematic integration of travel-time-based accessibility measures into equitable spatial prioritization of recreational green areas. It can help urban planners to identify sets of green areas that best support the recreational needs of the residents across the city.

1. Introduction

To date, the role of urban nature and green spaces in supporting citizens' health and well-being has been widely acknowledged (Ayala-Azcárraga, Diaz, & Zambrano, 2019; Cox, Shanahan, Hudson, Fuller, & Gaston, 2018; Ekkel & de Vries, 2017; Norwood et al., 2019). However, the daily use of green areas is dependent on their accessibility and quality (e.g. facilities or vegetation structure) (Ayala-Azcárraga et al., 2019; Luz et al., 2019; Massoni, Barton, Rusch, & Gundersen, 2018; Vierikko et al., 2020; Wang, Kotze, Vierikko, & Niemelä, 2019; Zhang & Tan, 2019). Equitable accessibility to green areas among all residents is one of the major components in building socially sustainable cities (Dale & Newman, 2009; Du & Zhang, 2020; Ferguson, Roberts, McEachan, & Dallimer, 2018; Kabisch & Haase, 2014; Kimpton, 2017; Nesbitt, Meitner, Girling, Sheppard, & Lu, 2019; Pearsall & Eller, 2020; Wolch, Byrne, & Newell, 2014).

Analyses of fair access to green areas are often focused on finding districts of green area deprivation, thereby identifying target districts for greening and the establishment of new green areas (Dai, 2011; Kimpton, 2017; Liu, Chen, & Dong, 2017; Rigolon, 2016, 2017; Wolch et al., 2014). However, in cities undergoing densification and growth, it may be more relevant to identify green areas that are the most important for maintaining equal green access at the city level, so that new development does not add to inequality in green area provision (Haaland & van den Bosch, 2015; Pearsall & Eller, 2020; Wei, 2017).

In this study, we (i) used spatial prioritization, an approach originating from spatial conservation science, to identify which urban green areas are the most important for equitable recreational accessibility throughout a city region. We then (ii) compared the results to a typical buffer analysis. Accessibility is based on travel times and calculated for different travel modes (walking, biking, public transport) and two recreation use types (local green areas and large recreational forests). We

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demonstrated the method in the Finnish capital region, Helsinki Metropolitan area, but it should be generally applicable to anywhere in the world.

1.1. Accessibility to green areas

The accessibility of green areas has been studied in different contexts and using different accessibility measures (Laatikainen, Piiroinen, Lehtinen, & Kyttä, 2017; Neuvonen, Sievänen, Tönnes, & Koskela, 2007; Reyes, Páez, & Morency, 2014; Rojas, Páez, Barbosa, & Carrasco, 2016; Rossi, Byrne, & Pickering, 2015), including Euclidean distance (De La Barrera, Reyes-Paecke, & Banzhaf, 2016; La Rosa, 2014; Neuvonen et al., 2007), network distances (Du & Zhang, 2020; Herzele & Wiederman, 2003; La Rosa, 2014), or travel times from people's homes (Chang & Liao, 2011; Laatikainen et al., 2017). Time-based accessibility metrics are considered to be better for describing human behavior than distance-based metrics (Apparicio, Abdelmajid, Riva, & Shearmur, 2008; Salonen & Toivonen, 2013). Willingness to travel to a green area depends on personal preferences and the type of the green area (Laatikainen et al., 2017; Neuvonen et al., 2007; Rossi et al., 2015), but in principle, the closer the green area is to people, the more likely it will be visited (the so called 'distance-decay' effect; Iacono, Krizek, & El-Geneidy, 2010; Liu et al., 2017). The relationships between distance and the likelihood of visits (i.e. distance-decay patterns) usually vary between travel modes (Iacono et al., 2010; Rojas et al., 2016). Likewise, the time people are willing to spend to reach their destination depends on the type of recreation intended in the green area (Laatikainen et al., 2017). Therefore, when analyzing accessibility of green areas at the level of an entire city, it is important to separate the accessibility of different types of green areas and account for travel modes that are associated with different types of recreation behavior (Laatikainen et al., 2017; Liu et al., 2017).

1.2. Spatial conservation prioritization

The difficulty of defining the relevance of areas for protection is a common question in nature conservation science. There are two main approaches for defining the conservation importance of areas: scoring and complementarity-based spatial prioritizations (Kullberg et al., 2015; Veach, Di Minin, Pouzols, & Moilanen, 2017). Heuristically explained, scoring describes the conservation value of a location as some kind of sum over absolute metrics, such as species richness, that can be measured locally (Veach et al., 2017; Williams, 2000). One intuitive approach to defining the importance of individual green areas for city-level accessibility is to score them according to the number of people living within a distance or time buffer (Annerstedt Van Den Bosch et al., 2016). Although scoring is a rapid and intuitive approach, and it provides important information about usage pressure for green area management, it does not include any information about *who* lives in the proximity of a given green area, and whether those people have

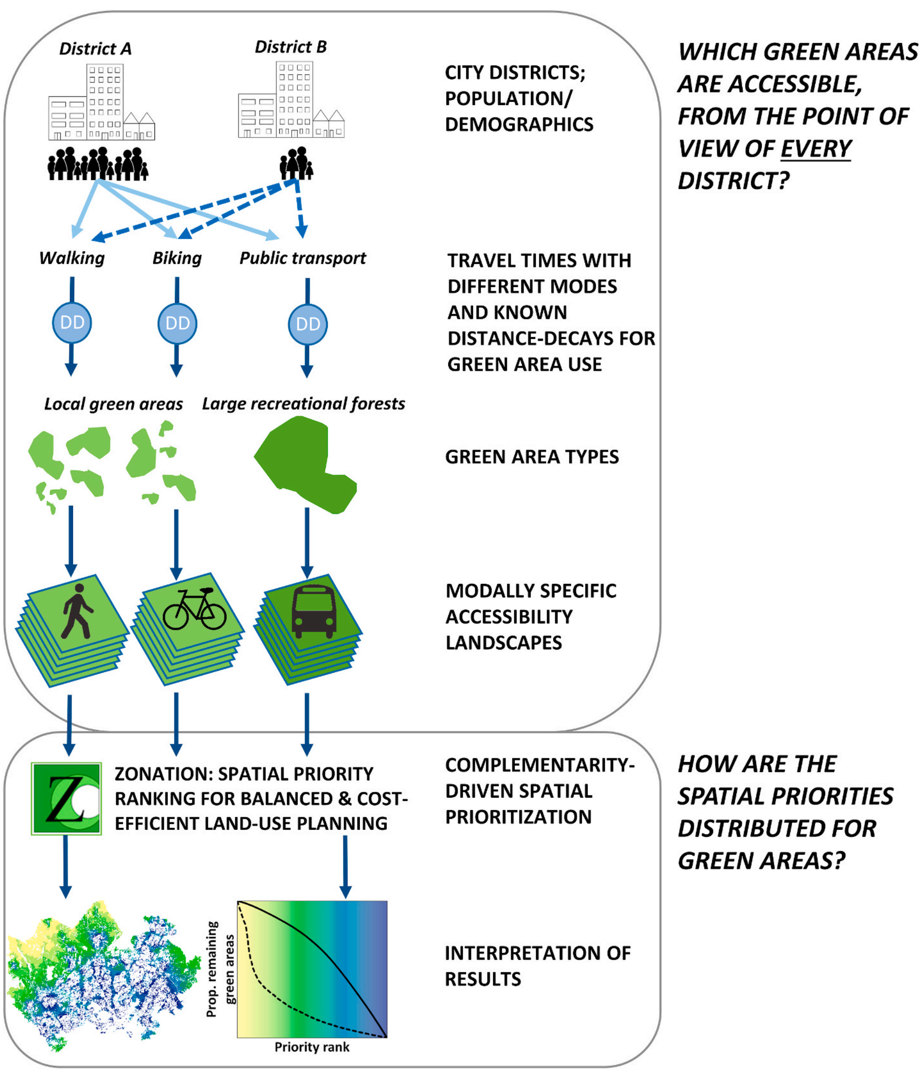

Fig. 1. Study design for fair accessibility from different districts by using different mobility modes (3) and known distance-decays (DD) separating two types of recreational green spaces: local green areas and large forest areas. Spatial prioritization of recreational green spaces is based on modally specific accessibility landscapes and implemented by using the Zonation software. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

many other green areas within their accessibility range. Generalized over the entire city, this approach could therefore lead to three problems from the perspective of equality. First, the approach neglects those green areas that would be the only accessible ones but only for a comparatively small number of people. This could be the case with people who live next to wide and dense commercial or industrial areas with only few parks in the vicinity. Second, the approach misses the fact that two nearby green areas may provide recreation opportunities mainly to the same people, especially if the provision of green area amenities is taken into account (Kimpton, 2017). Third, because of the previous two, if accessibility to green areas, defined as the number of nearby residents, would be balanced against for example urban biodiversity or ecosystem services, green areas that are important for only a few people could become neglected.

Compared to scoring, complementarity-driven spatial prioritization methods provide a different view of prioritization. The complementarity principle in spatial prioritization means the aim to rank the target landscape from "less" to "more important" parts while, importantly, maintaining a balanced coverage of all input features (i.e. the objects that are desired to be conserved, such as species' ranges or ecosystem services) (Kukkala & Moilanen, 2013). Instead of identifying the areas of highest richness or "hotspots", spatial prioritization is used to identify sets of areas that would jointly protect the most of input features. Usually, high-priority areas identified with spatial prioritization include both high feature richness and/or existence of (relatively) rare features (Moilanen et al., 2005; see also Section 2.6). Complementarity-driven spatial prioritization generally results in higher coverage of protected features than scoring (Kullberg et al., 2015; Veach et al., 2017), and in the past two decades, spatial prioritization has become widely used in conservation planning (Sinclair et al., 2018). Spatial prioritization has been utilized in many environments including urban areas (Bekessy et al., 2012; Cimon-Morin & Poulin, 2018; Jalkanen, Vierikko, & Moilanen, 2020), and some prioritizations have included an accessibility element with other components, including distributions of biodiversity, threats and costs (Bekessy et al., 2012; Cimon-Morin & Poulin, 2018). Spatial prioritization could therefore mitigate the three problems inherent in scoring. Hence, here we proceeded from the assumption that spatial prioritization could be used to locate the most important sets of green areas for the equitable (i.e. balanced) access of all urban residents. This approach resembles a protocol to the maintenance of equitable access to ecosystem services in spatial prioritization (Verhagen, Kukkala, Moilanen, van Teeffelen, & Verburg, 2017).

2. Materials and methods

2.1. Study design

The workflow for the study consisted of two main parts (Fig. 1). First, we estimated how accessible each green area (from CORINE land cover; Section 2.3.) is for the residents by using modeled travel time data (Section 2.4.) and known distance-decays for green area visits (Section 2.5.). Importantly, accessibility of green areas was calculated separately and systematically from the point of view of every urban district, which enabled systematic balancing across green areas. Accessibility was calculated separately for everyday recreation (i.e. using travel times for walking and biking to all green areas) and nature-oriented recreation (i.e. public transport to large forests at the metropolitan fringe). Finally, using accessibility maps as input layers, all green areas were prioritized using the Zonation software (Section 2.6.). To demonstrate the differences between scoring and complementarity-based prioritization, we compared the spatial prioritization maps with a typical scoring map that showed the population within a 500 m buffer from each green area.

2.2. Study area

Because of its 1.4 M population, the Helsinki Metropolitan area (770 km2) is the greatest urban region in Finland. It consists of four municipal cities, Helsinki (capital city of Finland), Espoo, Vantaa, and Kauniainen, which are further divided into total of 185 city districts.

On the European scale, the Helsinki Metropolitan area still has a relatively high density of green areas (Pauleit et al., 2019). Small green areas (<2 ha) exist throughout the metropolitan area, but also larger

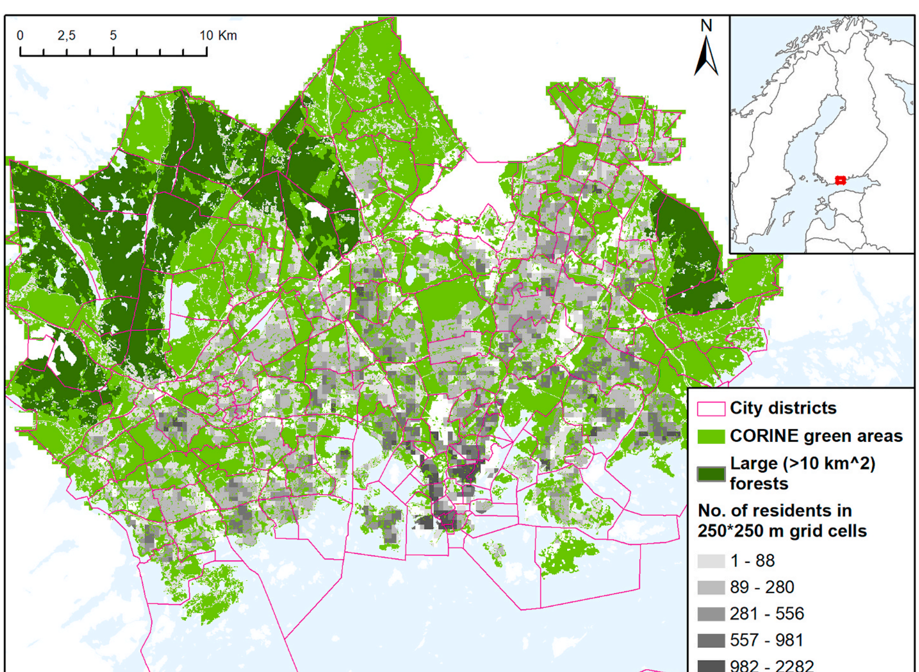

Fig. 2. Green areas, city districts, and population density in the Helsinki Metropolitan area. Extensive green areas exist at the urban fringe, but there are many green areas of different types and sizes in inner-city areas as well. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ones (from over 10 ha to several km^2) expand to near the urban center (Fig. 2). In addition, the metropolitan area has an extensive rural-like urban fringe. Large forests on the outskirts of the metropolitan area, including two national parks, have infrastructure for nature-oriented recreation (e.g. trails, campfire places).

The Helsinki Metropolitan area is subject to major growth and its population is expected to grow by 600,000 (~40%) by 2050 (e.g. Laakso, 2012). The inevitable loss of green areas due to urban expansion and densification highlights the need for socially equitable prioritization of green areas.

2.3. Data about green areas

We mapped the local green areas using the CORINE Land Cover 2018 raster map (EEA, 2018), from which we excluded all built-up land cover classes and water areas (i.e. classes 1–11, 16, 47–49). As a result, all types of urban green were included into our analyses (Fig. 2), which is important because all accessible green areas cumulatively contribute to people's well-being (Ekkel & de Vries, 2017). As a proxy for nature-oriented recreation areas, we used contiguous forests (from CORINE) that were over 10 km^2 large. The spatial resolution for both raster maps was 20 by 20 m.

2.4. Population & travel time data

Finnish state officers provide demographic data throughout Finland, aggregated to a 250 m grid vector layer ('POP grid' hereafter). For the Helsinki Metropolitan area, travel times between all grid squares were available in an open data product called the Helsinki Region Travel Time Matrix (Tenkanen & Toivonen, 2020). This longitudinal dataset contains travel time and distance information between all 250 m POP grid cell centroids in the metropolitan area. The dataset is multimodal and multitemporal by nature: all typical transport modes (walking, cycling, public transport, and private car) are included following so-called door-to-door principle, making the information between travel modes comparable. Travel times and distances were calculated with a routing algorithm that takes into account the real local road and public transport network (Supplementary Figs. S1 and S2, respectively) and public transport schedules; see Tenkanen and Toivonen (2020) for details. Biking was calculated separately for slow and fast speeds (received from typical local biking speeds). Public transport was calculated separately for rush hour and midday on an average working day. The values are available for three years (2013, 2015, and 2018). We used the 2018 midday values for public transport and slow biking time in this analysis.

2.5. Defining the accessibility of green areas

We treated the typical proportions of travel times that local people

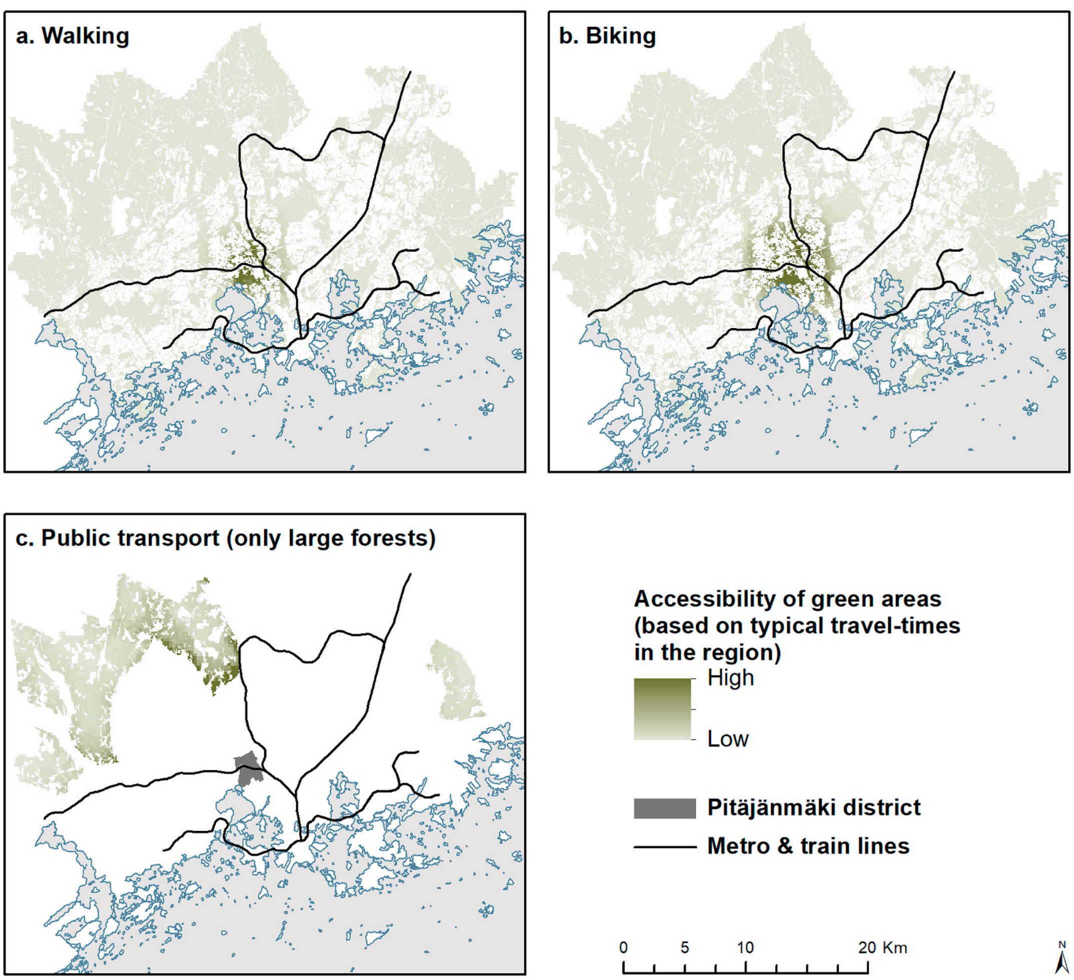

Fig. 3. Illustration of accessibility of green areas in Helsinki Metropolitan area, from the perspective of the Pitäjänmäki district. Accessibility is based on modeled travel times that are compared to typical times spent by local people going from home to a recreational area by (**a**) walking, (**b**) biking, and (**c**) using public transport to large (>10 km^2) recreational forests. For the sake of visual clarity, the Pitäjänmäki area is shown only in (**c**). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

generally spend (i.e. the local distance-decay functions of each travel mode) as a proxy of the accessibility of green areas. We estimated the distance-decay functions by using the data from the recent travel survey by the local planning authority (Brandt, Kantele, & Räty, 2019). In the survey, 10,924 respondents kept a travel journal for one pre-defined day and recorded, among other information, the time spent, travel modes used, origin, and destination for each trip. We calculated these distance-decay functions with R (R Core Team, 2019), separately for walking (Supplementary Fig. S3, Supplementary Table S1), biking (Supplementary Fig. S4, Supplementary Table S2), and public transport (Supplementary Fig. S5, Supplementary Table S3); see Supplementary S1 for details. Here, the distance-decay functions were used to predict the accessibility of green areas based on travel times needed to reach them (see below). For example, the number of walking trips decreases rapidly as the walking-time increases (Supplementary Fig. S3), meaning that a given green area must be rather close to residents to be considered as accessible on foot (see also Fig. 3).

We iteratively estimated how accessible each green area cell was for every city district (Fig. 1) using R (R Core Team, 2019). We summarized the travel times at the level of city district to (i) limit the number of input layers used in prioritization, thus making the analysis computationally more convenient, and (ii) because districts are common and intuitive units for summarizing green area provision compared to individual 250 m grid cells. We took the minimum travel time *T*, received from the Travel Time Matrix (in minutes), from all POP grid cells within the given district (every POP grid cell was assigned to the district inside which its centroid was) to every other POP grid cell. We used the minimum value instead of median, because the minimum value more realistically showed which green areas are accessible for at least some of the district's residents, especially in sparsely populated districts on the urban fringe, whereas median value would place the "accessible" green areas only around one location within a broad district. We then applied the travel mode-specific distance-decay function *f* (see above) to the travel time value *T* (with the respective travel mode) from the district to every POP grid cell. Finally, we assigned the resulting proxy value of accessibility *f*(*T*) to the green area cells within each POP grid cell (i.e. inside of which their centroid was). As a result, we got a raster map of the green areas with cell values giving the accessibility from the given district (based on the travel times and distance-decays). This procedure was repeated for every city district with permanent residents (n = 181; not all districts have permanent residents), which allowed spatial prioritization that systematically balanced between green area provision for all districts. Three raster maps were produced per district: accessibility to all green areas by (1) walking and (2) biking, and (3) accessibility to large forests using public transport. Fig. 3 shows an example of the accessibility of green areas, from the perspective of one district.

To compare the differences between complementarity-based spatial prioritization and scoring, we created a typical "buffer map" that showed the sum of people (from POP grid) living inside a 500 m buffer around each green area cell.

The R codes for defining the distance-decay functions and preparing the accessibility layers and buffer map can be found in Zenodo (https://zenodo.org/record/4022597).

2.6. *Spatial prioritization with the zonation software*

We used the Zonation software for spatial prioritization of green areas (Lehtomäki & Moilanen, 2013; Moilanen et al., 2011, 2005), using the accessibility of green areas as input layers. Zonation first assumes that best for every input feature (in our case, city districts and their residents) would be that all green areas would be protected. It then iteratively removes grid cells that result in smallest marginal loss over all features and produces a balanced and complementarity-driven priority ranking of the target area. In other words, Zonation balances in-between green area provision for all districts simultaneously and tries to maintain as much accessible green areas for every district for as long as possible throughout the prioritization process. Zonation has several options for how balancing between features is implemented during prioritization. We used the *Core Area Zonation* option, which emphasizes balanced coverage of high-quality areas for each feature, meaning here that all districts have as good access to recreation as possible (Lehtomäki & Moilanen, 2013). Overall, green areas receive highest priorities if they are the only accessible ones for some districts. In contrast, if the district has easy access to many green areas, then the relative importance of those green areas becomes lower. Input layers can be assigned individual weights in Zonation (Moilanen et al., 2011). Then, the priority rank becomes determined by a combination of input layers' relative rarities and weights.

Zonation's two main outputs are the priority rank map and so-called performance curves. The rank map is a raster map with linearly scaled values from 0 to 1. The higher the priority of a green area, the more important it would be for the equality of accessibility at the level of the whole city (i.e. it is accessible from many districts, and/or for a district that does not have good access to other green areas). Performance curves follow the district-specific proportions of the accessible green areas from the original level throughout the ranking process. In the case of this work, the curves can be used to assess how well different top-priority fractions of green areas support recreation for different districts. For example, linearly decreasing curves would indicate that accessible green areas are very evenly distributed across all city districts. Starting from linear, the more convex the curves are, the bigger the differences are in the value of different green areas for recreation.

We prioritized the green areas in the Helsinki Metropolitan area in phases. First, we did the prioritization separately for walking and biking and then for the two travel modes together. We did separately weighted and non-weighted versions of each analysis. For the weighted versions, each input layer received as a weight the number of residents in the focal district.

To demonstrate that different types of green areas can be included in spatial prioritization analyses, we included public transport-based accessibility to large recreational forests. As a result, the priority patterns would be better balanced between the provision of both local green areas for everyday use, and large forests for nature-oriented recreation.

To compare the spatial prioritization approach with the population-based buffer analysis, we did a simple overlay analysis and examined how evenly the two approaches distribute priority areas across the entire metropolitan area.

All Zonation setting files can be found in Zenodo (https://zenodo.org/record/4022597).

3. Results

3.1. *Spatial prioritization vs. buffer-based scoring*

Figs. 4 and 5 show the distribution of priority areas using two different approaches. Fig. 4 shows the spatial priorities for local green areas separately for walking and biking accessibility, and for the two travel modes together. The buffer map of Fig. 5 shows how many people live inside a 500 m buffer around each green area pixel. The prioritizations with no population weighting (Fig. 4a, c, e) place top-priorities very evenly across the metropolitan area, compared to the buffer map, which is highly driven by population density. In the population-weighted prioritization versions (Fig. 4b, d, f), priorities aggregate to the central green areas, but they nevertheless retain a few small top-priority sites on the outskirts of the metropolitan area. Based on the performance curves, the unweighted priority rankings (Fig. 4a, c, e) "are able" to preserve the accessible green areas closer to equally between districts as the curves decline following more a uniform trend. In the population-weighted versions (Fig. 4b, d, f), the differences between individual curves are much bigger, indicating that Zonation "had" to compromise the recreation opportunities for some districts (namely the least-populated ones) for the benefit of others (more populated ones). At

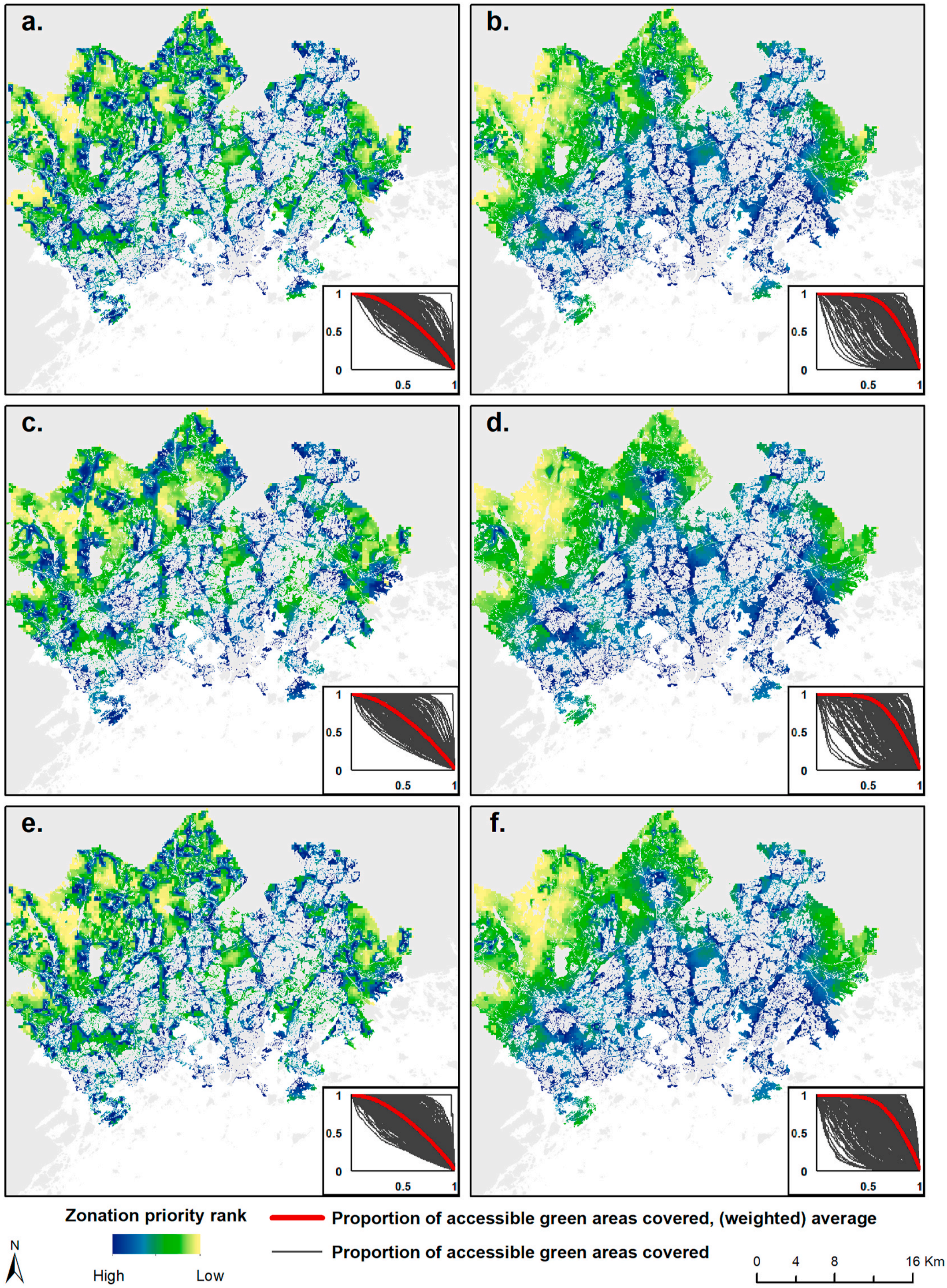

Fig. 4. Priorities of green areas in the Helsinki Metropolitan area based on their estimated accessibility to residents of different districts by (**a**–**b**) walking, (**c**–**d**) biking and (**e**–**f**) both travel modes, without (**a**, **c**, **e**) and with (**b**, **d**, **f**) district-specific population weights. The analysis-specific performance curves (lower-right corners) show the proportions of the original accessible green areas (y-axis) covered by different top-priority fractions of the ranked landscape (x-axis). Performance curves are drawn separately for every district (grey curves) and for the average (weighted average in the population-weighted versions) of all districts (red curve). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the scale of the entire population, some green areas are much more responsible for provision of recreation than others, which show as convex performance curves.

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3.2. *Inclusion of large forests and public transport -based accessibility*

Inclusion of large recreational forests as an additional target of prioritization changed the priority patterns, especially in the population-weighted version. Fig. 6 shows the spatial prioritization analyses (i) for large forest areas, based on their accessibility using public transport (Fig. 6a and b) and (ii) for all travel modes and both green area types

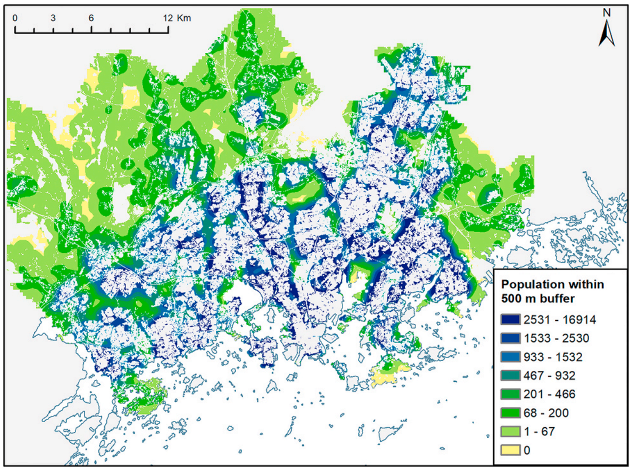

Fig. 5. Population within a 500 m buffer of each green area in the Helsinki Metropolitan area. Note that the visualization by quantiles (of cell counts) decreases the skewness of the actual values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

simultaneously (Fig. 6c and d). As expected, the priorities at the accessible parts of large forests increase. Spatial prioritization is able to find a synergistic balance between the two green area types, especially in the version without population-based weighting, as the priority patterns are roughly the same with and without large forests (Figs. 4 and 6, respectively). The priorities of large forests rose more clearly in population-weighted versions of the analyses, in which top-priorities included those parts of both central green areas and recreational forests that were the most accessible for the most populous districts of the metropolitan area (Figs. 6 and 4, respectively). A notable detail in the performance curves is that public transport serves all districts close to equally well, as shown by the small differences in the shapes of individual curves.

3.3. Comparison of the spatial distribution of top-priorities between different methods

There were important differences in the priority patterns between spatial prioritization and the buffer analysis. Fig. 7 shows the results of an overlay analysis in which we compared how many city districts included green area cells inside them, if only the top10% of green areas would be accounted for. We compared the population-weighted spatial prioritization for walking and biking (Fig. 7a), population-weighted spatial prioritization analysis for all travel modes, and two types of green areas (Fig. 7b), and typical buffer analysis (Fig. 7c). Spatial prioritizations place the top-priority fragments more evenly across the metropolitan area than buffer analysis. The number of districts (out of 181) that had top10% green areas inside them was 138 for prioritization for walking and biking, 142 for prioritization for all travel modes and both green area types, and 121 for buffer analysis. Furthermore, as shown in Fig. 6, spatial prioritizations "spread" the top-priority sites more to the outer districts than the buffer analysis does. Nevertheless, most of the green areas identified as important by spatial prioritization as well, are located in the central and most populated districts of the metropolitan area.

4. Discussion

This paper describes an approach for identifying the most important recreational urban green areas in terms of fair access. Unlike earlier studies about equality in access to green areas, we based our analysis on spatial prioritization (e.g. Kabisch & Haase, 2014; Wolch et al., 2014). Major components in the approach are the spatial data for green areas of different recreational usage, population registry data and the modeled travel times from people's homes to all green areas, using appropriate transport modes. Also needed are distance-decay functions that describe how long people are willing to travel using different modes of travel. These data can be entered into complementarity-driven spatial prioritization, which allows a balancing of the recreational needs of all city districts.

Compared to the traditional buffer-based analysis, our approach acknowledges realistic travel times with different modes, as well as the fact that there are different recreational needs (local parks vs. forest parks in our case). Due to the complementarity principle applied in the spatial prioritization, top-priority parks become located more evenly across the study area than typical buffer analysis suggests (Fig. 7). Even if the starting points of accessibility calculations are people's homes, top-priority sites are found also on the outskirts of the metropolitan area, where the most accessible green areas are located for some residents (Fig. 7). This is an expected outcome, because the complementarity principle should ensure that people in the urban fringe, even if their numbers are much smaller than in the city center, should not be forgotten in terms of green area provision. In turn, this translates into greater equity in provision of accessible green areas at the metropolitan level compared to what is proposed by simple population metrics, as the central green areas are of little value to the people living on the metropolitan outskirts, at least when considering daily outdoor activities. The performance curves (Figs. 4 and 6) allow assess to the amount of accessible green areas at different spatial priority levels for each district. During our pilot runs, we verified that spatial prioritization is influenced by the shape of the distance-decay curves, as it should be. Hence, attention should be placed on the estimation or definition of approximately realistic travel time decay functions. If the time decay is too steep, priorities will tend to aggregate close to where people live. If the decay function is too flat, priorities will be identified in far-away locations that people realistically will not go to.

Spatial prioritization results (Figs. 4 and 6) can support urban planning to account better for fair access to green areas by all residents living in different districts and regardless of their socio-economic status (Nesbitt et al., 2019). Green areas of highest priority should be preserved, because they jointly support the accessibility of most people in the Helsinki Metropolitan area. The very top-priority sites, including those being parts of larger green areas, could be seen as the primary target areas for placing and/or improving recreational amenities because they act as the key accessibility spots across the metropolitan area. On the other hand, low-priority areas would be most suitable for urban expansion following the principle of impact avoidance (Kareksela, Moilanen, Tuominen, & Kotiaho, 2013). The Zonation approach can also support impact assessment of urban development plans, by investigating what is in the areas where green will be lost (Jalkanen, Toivonen, & Moilanen, 2020; Moilanen et al., 2005).

The main limitation of our method is the demand for heavy computation for calculating accessibility information like the Travel Time Matrix (Tenkanen & Toivonen, 2020). Realistically accounting for future land use (e.g. comparison of different land use scenarios) would require further accessibility calculations for the future situations. However, simpler accessibility measures could work as inputs of spatial prioritization as well, if accessibility to green areas is calculated separately, systematically, and realistically for all target city sub-areas. Furthermore, it is important to remember that priority rank maps (Figs. 4 and 6) only allow for evaluation of the importance of green areas on a relative scale (Lehtomäki & Moilanen, 2013) and by themselves do not provide any absolute metrics for estimated user counts, for instance. Straightforward population-based metrics remain useful for many purposes, including estimation of usage pressure for green area management (Lehvävirta & Rita, 2002), statistical factors in quantitative studies regarding green areas (Wang et al., 2019), or quick estimation of the population having access to green areas for international comparisons (Annerstedt Van Den Bosch et al., 2016).

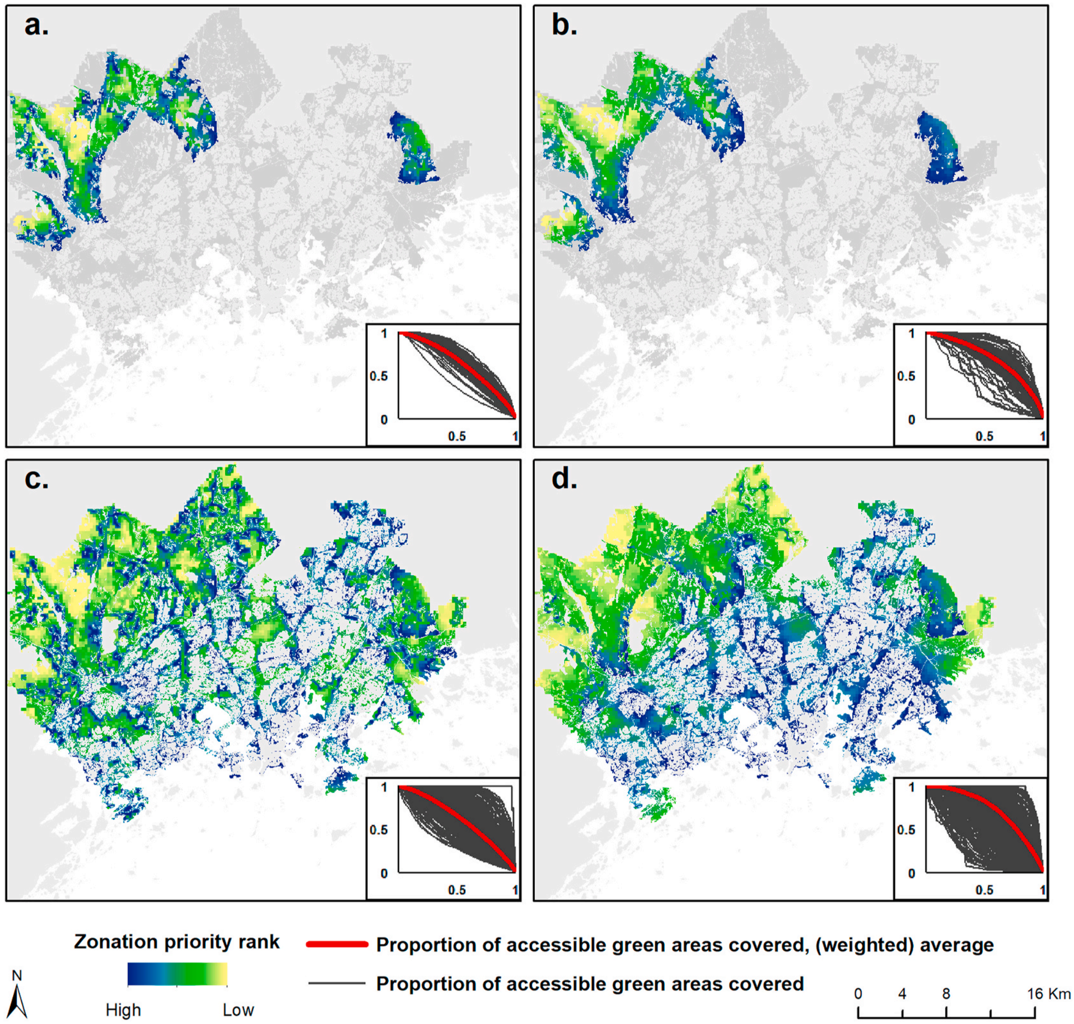

Fig. 6. Priorities of (**a**–**b**) large forests and (**c**–**d**) all green areas (including large forests) in the Helsinki Metropolitan area based on their estimated accessibility by public transport (**a**–**b**) or by the relevant travel modes per area (walking and biking for local green areas, public transport for large forests), without (**a**, **c**) or with (**b**, **d**) district-specific population weights. The analysis-specific performance curves (lower right corners) show the proportions of the original accessible green areas (y-axis) covered by different top-priority fractions of the ranked landscape (x-axis). Performance curves are drawn separately for every district (grey curves) and for the average (weighted average in the population-weighted versions) of all districts (red curve). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

There are ways to refine our present spatial prioritization analyses. We used only two types of green areas: all local green areas and large recreational forests (Fig. 3). In reality, local green areas may consist of several sub-types that are not fully equivalent in terms of recreation. Most of the local green areas in the Helsinki Metropolitan area are semi-natural forests that support a range of types of recreation than e.g. managed parks (Jalkanen, Vierikko, & Moilanen, 2020). It could thus be reasonable to further divide local green areas into e.g. semi-natural areas, managed parks, and water areas, and calculate accessibility to them separately.

We used only two travel modes for local parks and public transport for larger forests. If a large forest is a neighborhood park, the travel time is essentially the walking time directly to the forest instead of taking a bus. The travel time data would also have allowed considering the use of private cars, time of day, or biking speed. The private car option was excluded because the objective was to analyze equitable access irrespective of car ownership. The analysis could also be targeted to a selected subset of the population such as elderly people or children (Neuvonen et al., 2007). Furthermore, we used one generalized distance-decay function per travel mode (Section 2.4.; Supplementary Figs. S3–S5). Distance-decay functions could be made different between different green area types (Laatikainen et al., 2017). Distance-decay, meaning ultimately friction of travel, could also be different depending on the population group. If the data are available, our framework could easily accommodate different travel modes and distance-decays for children, adults, and elderly people, which would add to the realism of the prioritization from the perspective of equality. The population size of each demographic group should then be reflected in the weighting of input layers. If the proportions of people who prefer a particular travel mode are known (e.g. those who prefer biking vs. public transport), those proportions could also be accounted for in the weights. If the city of interest has guidelines regarding green area provision, such as that every resident should have at least 1 ha within a 300 m walk (Annerstedt Van Den Bosch et al., 2016; Kabisch & Haase, 2014), they could be built into spatial prioritization as so called targets. This would allow using prioritization software other than Zonation, such as MARXAN (Ball & Possingham, 2000).

One could also account for the sizes of green areas in spatial prioritization. The relative importance of small green area patches, if considered less relevant for local analyses, could be reduced by using the so-called condition layer in Zonation (Kujala, Lahoz-Monfort, Elith, & Moilanen, 2018). If desired for administrational purposes, spatial

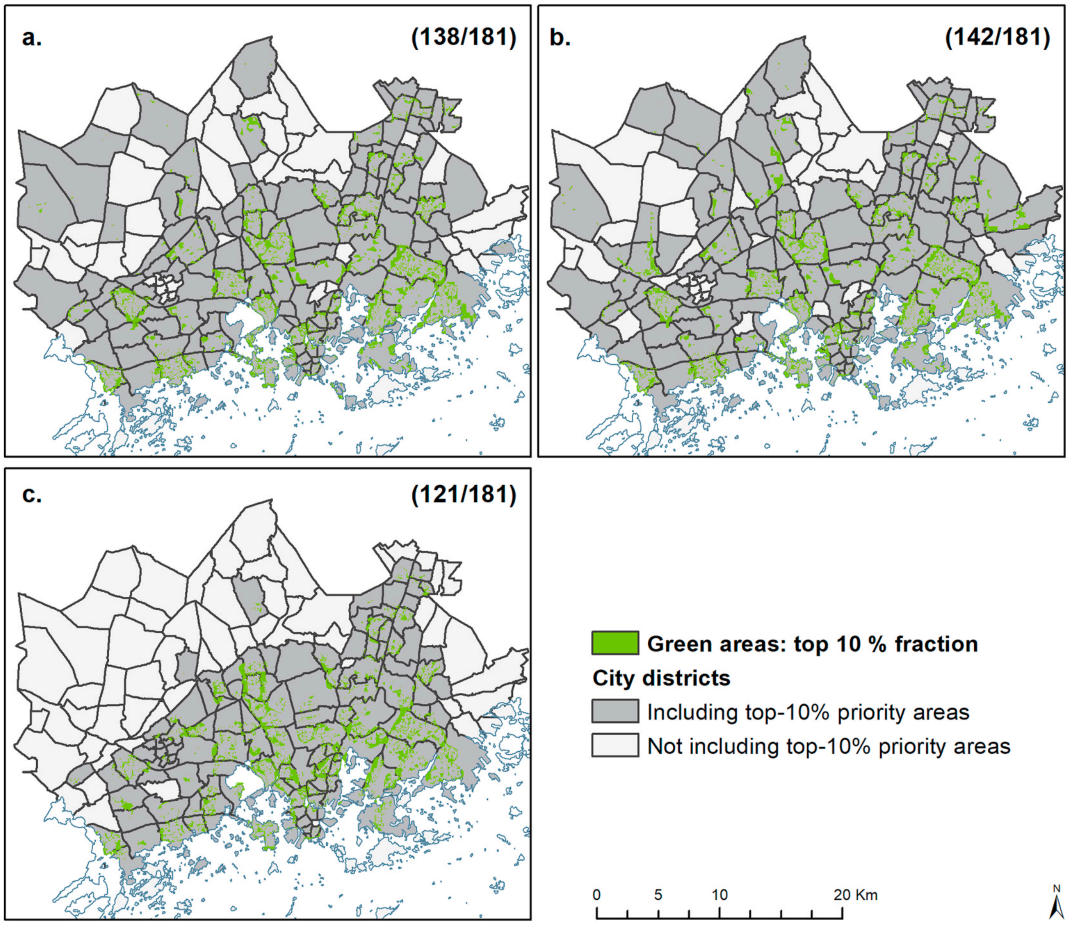

Fig. 7. Helsinki Metropolitan area districts that include top10% green area cells in the prioritization analyses of (**a**) local green areas given their population-weighted accessibility from city districts (by walking and biking), (**b**) all green areas including large forests given their population-weighted accessibility from city districts (accessibility estimated by walking and biking to local green areas, and by public transport to large forests), and (**c**) all green areas given their population within a 500 m buffer. The numbers in parentheses show the number of city districts (out of all 181) that have top10% green area cells. Complementarity-based spatial prioritization locates the same amount of land in a more balanced way across the metropolitan area than typical population-based buffer analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

prioritization could be done for green areas as a whole instead of single pixels by using the so-called planning units method in Zonation (Moilanen & Arponen, 2011). Another potential planning approach would be comparing different urban fabrics (walking, public transport and car dependent) and whether accessibility to green areas is equal between these (Newman, Kosonen, & Kenworthy, 2016). Although such elaborations would increase realism somewhat, they go beyond the scope of this paper, the aim of which was to demonstrate the general approach to the use of spatial prioritization to balance accessibility to green space when urban expansion threatens to eat into remaining green areas.

We highlight that our results should be interpreted with caution. For example, priority rank maps should always be interpreted with the respective performance curves; maps alone cannot be used to assess which priority level could be considered *adequate* for residents. Implementation of prioritization should be planned carefully (Knight, Cowling, & Campbell, 2006). Reallocation of green areas may cause resistance among property owners, for example because the proximity of green areas often affects property values (Du & Zhang, 2020). Naturally, real-life urban planning should also respect the different qualities, assets, popularities, and requirements of different green areas. The real value of a green area to urban people is not determined only by its (modeled) accessibility (Ayala-Azcárraga et al., 2019; Kabisch & Haase, 2014; Zhang & Tan, 2019). For example, iconic historical parks in the center of Helsinki attract large numbers of people irrespective of the travel time required. On the other hand, large forests on the fringe of the Helsinki Metropolitan area should remain large and in natural condition to support nature-oriented recreation in the future. Furthermore, it is notable that the population-weighted prioritization of local green areas especially allocated the lowest priorities at the urban fringe (Fig. 4f), which, in a growing city, could be seen as promoting urban sprawl (Koprowska, Łaszkiewicz, & Kronenberg, 2020). If sprawl to the urban fringe or other growth restriction areas is undesired, they could be simply excluded from the analysis, or preferably included as a hierarchical mask in prioritization (Mikkonen & Moilanen, 2013). In that case, the highest priorities become "forced" into the growth restriction areas.

Fair access for all citizens is not the only priority in preserving green area provision (Jerome, Sinnett, Burgess, Calvert, & Mortlock, 2019). For example, a recent spatial prioritization in the Helsinki Metropolitan area by Jalkanen, Vierikko, and Moilanen (2020) showed that forests on the metropolitan fringe are important for local urban biodiversity. The method presented in this paper would allow systematic balancing between human access and urban biodiversity, based on the addition of distribution layers for species and habitats into the analysis. Maps for provision of and demand for ecosystem services could also be included (Cimon-Morin & Poulin, 2018). Nevertheless, the present analysis brings one useful piece of information to urban planners and managers of green areas.

5. Conclusions

One great challenge in growing cities is to ensure fair access to green areas for all residents, at the level of the entire city. Spatial prioritization, often used in spatial conservation planning, allows systematic assessment to identify the green areas that are the most important for equitable accessibility to recreation. Our method could be combined with other types of data in prioritization, such as distributions of biodiversity, other ecosystem services, threats, or costs. Thus, the method could provide a more comprehensive understanding of urban green areas and their importance for the people and biodiversity.

CRediT authorship contribution statement

Joel Jalkanen: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Validation, Visualization, Writing - original draft, Writing - review & editing. **Henna Fabritius:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Project administration, Validation, Writing - original draft, Writing - review & editing. **Kati Vierikko:** Conceptualization, Funding acquisition, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Atte Moilanen:** Conceptualization, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Tuuli Toivonen:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Validation, Visualization, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2020.102320.

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